Amorphous Metal Ribbons and Metal Amorphous Nanocomposite Materials Enabled High-Power Density Vehicle Motor Applications

Product ID: ELT256

Principal Investigator & Presenter: Michael E. McHenry
Carnegie Mellon University

June 1, 2020

Overview

Timeline

State Date: September 19, 2019

End Date: March 18, 2022

Percent Complete: 20%

Budget

Total project funding $878,882

- DOE share $700,000
- Contractor %299,000 (includes CS)

BP1 10/19-12/20 $ 350,947

BP2 1/21-3/22 $ 527,935

Barriers / Technical Targets

The project aims at an 8-fold increase in power density in a (> 20 KW) traction motor showcasing Amorphous Metal Ribbon (AMR) & Metal Amorphous Nanocomposite (MANC) materials.

Current kW motors use Si-steels which are limited by losses to switching f < 1 kHz. New MANC technology adoption is hindered by: (a) limited US manufacturing; (b) materials limits for high frequency switching and (c) mechanical property constraints for certain motor applications

Partners

- NCSU: Subhashish Bhattacharya
- Metglas: Eric Theisen

Relevance - Objectives

- The objective of this project is to achieve 8-fold increase in power density for a traction motor designed to showcase Amorphous Metal Ribbon (AMR) and Metal Amorphous Nanocomposite (MANC) materials.
- A team from ***Carnegie Mellon Univ. (CMU), North Carolina State Univ. (NCSU)*** and ***Metglas, SC*** will design high speed motors (HSMs) with high-power density for traction motors.
- These are enabled by hybrid designs exploiting permanent magnets without heavy rare earths and high induction/high resistivity soft magnetic materials allowing for high switching frequencies needed to increase power densities.
- Magnetic switching frequencies of up to 5 kHz will be evaluated in the design to achieve 8x increase in power densities, motor speeds of 20 krpm (modeled to 40 krpm) and T rise of <50 ^{o}C at peak power.

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Relevance – Objectives II

- Technical components will be completed in two budget periods, BP1 and BP2:

- **Budget Period 1: Benchmark AMRs and MANC Alloys for Traction HSM Design:** AMR materials will be benchmarked, in a **Finite Element Analysis (FEA) model**. Alloys will be cast at commercial scale and properties relevant to 5 kHz magnetic core losses and audible magnetostrictive noise will be measured and compiled. Sample ribbons of each alloy will be provided to the DOE. **A FEA model of a Traction High Speed Motor (HSM) will be designed and performance evaluated**.

- **Budget Period 2: Properties Optimization, Component Fabrication and Alloy Studies.:** Properties of AMR materials will be optimized and benchmarked. Rotors and dual stators will be produced for testing and loss validation in the Flux Switching with Permanent Magnet (FSWPM) motor. Magnetic switching frequencies and mechanical properties will be evaluated. **Measured properties will be incorporated into a FEA model of a Traction HSM and used to finalize the design.** This design will be used to benchmark new materials.

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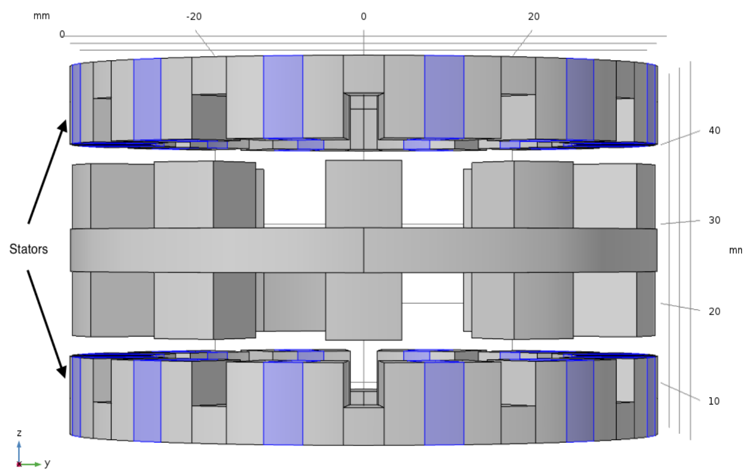
Approach

Benchmark 2.5 kW Design



Grey: Fe-Ni based MANC **Blue: Ferrite PM**

Novel Axial Motor Design: Flux Switching with Permanent Magnet (FSWPM) Motor

- 3-phase motor with Dual Stator & 14 Rotor Poles.
- 6000 rpm; 1.4 kHz switching; RE-free ferrite magnets.
- 80 mm outer & 50 mm inner radius
- 5.4 kg & 1.5 L envelope. 2.5 kW & 4.0 Nm torque.

Table I: Coercivity, saturation induction, thickness, losses at 1 T and 400 Hz, and losses at 1 T and 1 kHz for nanocrystalline $(Fe_{70}Ni_{30})_{80}Nb_4Si_2B_{15}$, nanocrystalline $Fe_{85}B_{13}Ni_2$, Fe-based Metglas 2605SA1, and non-oriented 3% Si-steel and 6.5% Si-steel. *H_c measured at 60 Hz and 1 T induction.

	H_c (A/m)	B_s (T)	t (μm)	$W_{1.0/400}$ (W/kg)	$W_{1.0/1k}$ (W/kg)
nc-$(Fe_{70}Ni_{30})_{80}Nb_4Si_2B_{15}$	7.0*	1.3	20	0.9	2.3
nc-$Fe_{85}B_{13}Ni_2$[38]	4.6	1.9	13.4	2.3	6.3
nc-$Fe_{89}Hf_7B_4$[39]	5.6	1.59	17	0.61	1.7
Fe-based amorphous[38]	2.4	1.56	23.9	1.6	4.7
3% Si-Steel[39,40]	55	2.05	100	8.5	27.1
6.5% Si-Steel[40]	18.5	1.85	100	5.7	17.2

	Fe-Ni MANC	3% Si-Steel
Fe loss: 2.5 kW	3.4 W	133 W
Cu loss (7.5 A)	27 W	27 W
Total	30 W	160 W
T-rise	27 ˚C	145 ˚C

Patented CMU, Fe-Ni based MANC

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Approach

- **Amorphous Magnetic Ribbon (AMR) and Metal Amorphous Nanocomposite (MANC) Materials as Benchmarked in (Sub-Task 1.2.1) Compared with Si-steel.**

	Power loss at 1T/1kHz (W/L)	Projected power loss in 2.5 kW FSWPM motor (W)	Maximum Flux Density (T)
Fe-3% Si	650	340	2.0
Co-based MANC	180	95	1.1
Fe-Ni(80%)- based MANC	17	9	1.3
Fe-Ni(85%)-based MANC	TBD	TBD	1.48
2605CO Metglas	190	100	1.80

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Approach - Milestones

Milestone	Description	Planned Completion Date	Actual Completion Date
Budget Period 1			
Design Traction Motor	Benchmark materials. Report FSWPM Motor Power Losses	6/15/20	
AMR Loss at 5kHz Evaluation Complete	Compare wide cast AMR and MANC Ribbon evaluation at 5 kHz	9/15/20	
Evaluate Materials in Traction Motor Design Ide	Complete Power Density Improvement Evaluation with AMRs and MANCs.	12/15/20	
Preliminary Design Validated to Achieve Performance Measures	FEA assessment of preliminary technology design has been completed, verifying an 8x increase in power density to be achievable.	12/15/20	
Budget Period 2			
Fabricate FeCo-based Dual Stators and Rotors.	Demonstrate Manufacturability of FeCo-based AMR motor.	6/15/21	
Evaluate Mechanical Properties of AMRs and MANCs Suitable for HSM	Use mechanical properties in FEA to verify that HSM is mechanically able to rotate at >20 krpm.	9/15/21	
Report Oxide properties for AMR and MANCs	Demonstrate resistance > coated laminates. Demonstrate Bulk resistivity > 150 mW-cm, surface resistivity > 500 mW-cm	12/15/21	
Test AMR and MANC Dual Stators and Rotors.	Report HSM power density for each material.	3/15/21	

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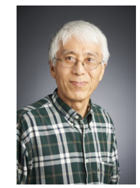
Collaboration and Coordination with Other Institutions





Principal Investigator Michael McHenry, 412-268-2703, mm7g@andrew.cmu.edu

CMU Co-Investigator	Prof. Maarten DeBoer
CMU Senior Scientist:	Satoru Simizu
Graduate Students:	Yuval Krimer, James Egbu, Kyle Schneider and Walter Robinson

Business Contacts: Rebecca Harrold, 412-268-4061, rebeccap@andrew.cmu.edu
Anthony Talotta. atalotta@andrew.cmu.edu


Partners:	NCSU	Subhashish Bhattacharya, sbatta4@ncsu.edu
	Metglas	Eric Theisen, Eric.Theisen@metglas.com

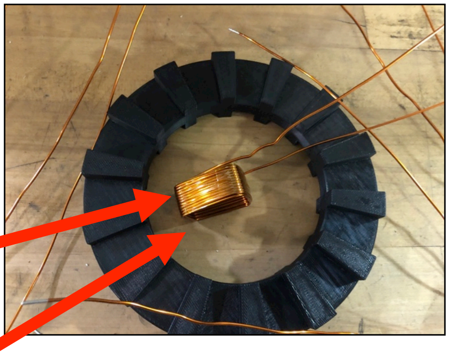
DOE VTO:	**John G. Tabacchi, NETL**	John.Tabacchi@NETL.DOE.GOV
	Amanda Lopez, NETL	Amanda.Lopez@NETL.DOE.GOV
	Susan Rogers, DOE EE	susan.rogers@ee.doe.gov

Technical Accomplishments and Progress

Sub-Task 1.1.1: Named Team
Sub-Task 1.1.2: Purchased FEA Software Modules for EM, Thermal and Mechanical Properties Modeling
Sub-Task 1.1.3: Identified Sources for permanent Magnets

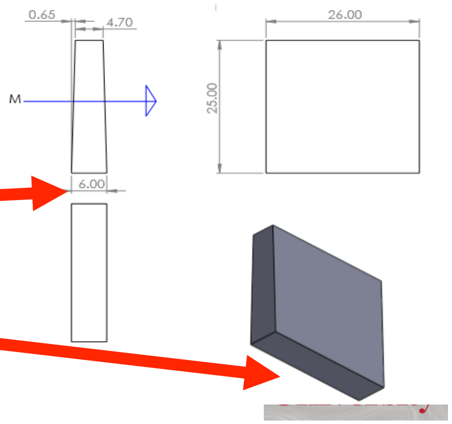
Sub-Task 1.2.1 Benchmark conductors, REPMs in FSWPM HSM Design

Conductor	Resisitivity (Ωm)	Power loss at 6 A/m^2 (W)	Density (kg/L)	Coil mass (kg)
Aluminum	2.5 x 10-8	52	2.70	0.16
Copper	1.6 x 10-8	34	8.96	0.52



50% Fill factor

Magnet type	Remanence (T)	Intrinsic Coercivity (kOe)	Magnet Size [tapered] (mm)	Comments
Ceramic 8	0.39	3.2	25 x 30 x [6.5 ~10.5]	
N38 (NdFeB)	1.20	12.0	25 x 26 x [4.7 ~ 6.0]	Dy: 0~1.5%



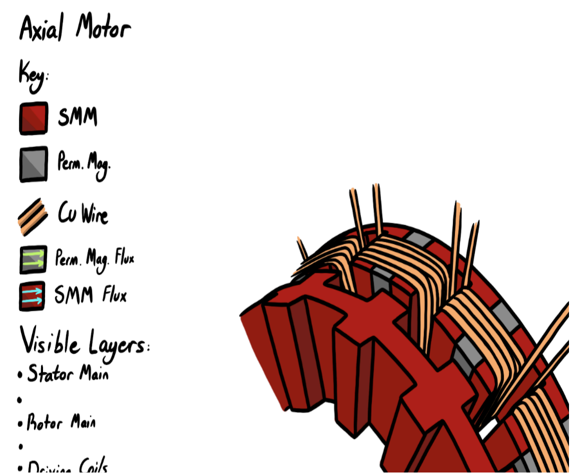
Sub-Task 1.2.4 Quote from Permanent Magnet Source: Quadrant

Technical Accomplishments and Progress

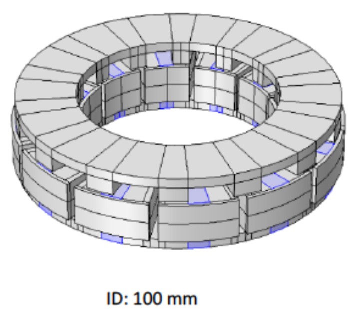
Sub-Task 1.2.2 Benchmark New Materials in prior FSWPM HSM Design

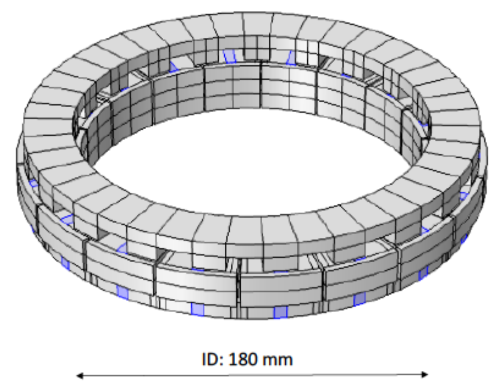
Enhancing specific power

Parameters	Initial (with verified material properties)	High power (with projected material properties)
Electrical Speed (at 6000 rpm)	1400 Hz	2100 Hz
Inner radius/outer radius	50 mm/80 mm	90 mm/115 mm
Flux density (peak)	0.60 T	1.53 T
Permanent magnet	Ferrite (B_r = 0.4 T)	NdFeB (B_r = 1.2T)
Current density (peak)	6.0 A/mm^2	18.0 A/mm^2
Conductor filling factor	46 %	60 %
Torque	4.2 Nm	59 Nm
Power (at 6000 rpm)	2.6 kW	37 kW
Copper loss (DC)	34 W (1.3 %)	230 W (1.3 %)
Iron loss (at 6000 rpm)	7 W (0.3 %)	82 W (0.2 %)
Motor mass	5.8 kg	9.9 kg
Specific power	0.45 kW/kg	3.8 kW/kg



2.5 vs. 20 kW Flux Switching with Permanent Magnet (FSWPM) axial dual stator high speed motors (HSMs).
Former is a 14-pole Motor the latter is 21 poles.
Former has ferrite (Br=0.4T) PM, latter NdFeB (Br=1.3T)
Latter exploits new higher induction MANCs
Latter operates at higher f, with larger radii

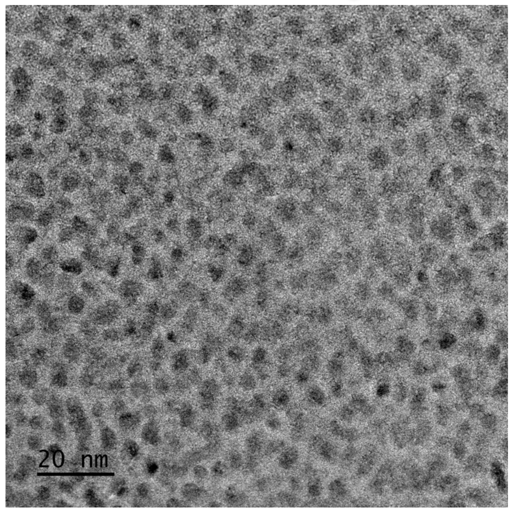




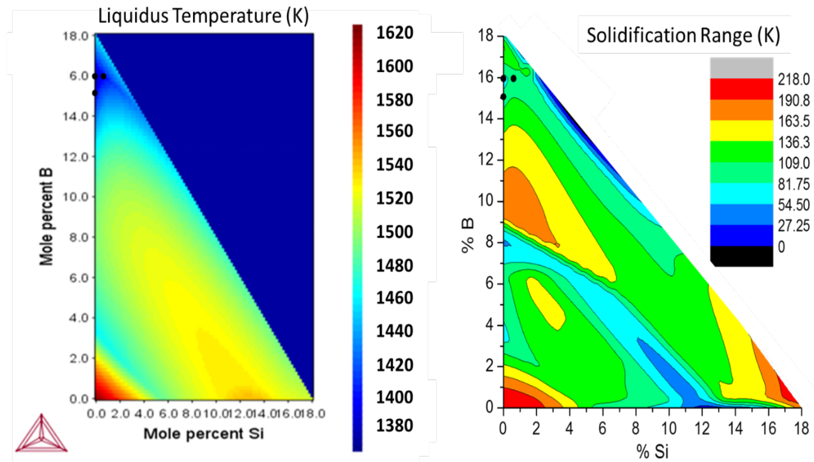
Technical Accomplishments and Progress

Sub-Task 1.2.3: Casting; Increased Inductions and Tc's in FeNi-based MANCs.

Direct casting into Nanocomposite for certain Alloys



Established Glass Forming Ability in Alloys with Increased FeNi



	$(Fe_{70}Ni_{30})_{82}B_{15}Si_0Nb_3$	$(Fe_{70}Ni_{30})_{82}B_{16}Si_0Nb_2$	$(Fe_{70}Ni_{30})_{82}B_{16}Si_1Nb_1$	$(Fe_{70}Ni_{30})_{85}B_{14.5}Nb_{0.5}Si_0$
$T_{c(amorphous)}$ (°C)	407	417	438	462
B (Tesla)	1.32	1.36	1.28	1.48
H_c (A/m)	37.6	30.0	30.7	26.0

Proposed Future Research

- **Task 1.3– Begin FeCo AMR Casting Trials, Measure Properties:**
- **Subtask 1.3.1 – Identify FEM topology and 2-d grids for traction HSM with > 5 kHz magnetic switching.**
- **Subtask 1.3.2 – Cast Metglas FeCo-based AMR in 2 inch wide ribbon for Evaluation.**
- **Subtask 1.3.3 - Measure Magnetostriction in Metglas FeCo-based AMR.**
- **Subtask 1.3.4 - Measure M(T), Bs, Tc, Crystallization temperatures and AC Losses.**
- **Task 1.4 – Screen Properties of MANC Alloys:**
- **Subtask 1.4.1 – Identify and Cast 2nd Generation FeNi MANC Alloy at Scale.**
- **Subtask 1.4.2 – Measure Bs, Tc, Crystallization Temp. and AC Losses for MANC.**
- **Subtask 1.4.3 – Measure Magnetostriction in FeNi-based MANC Alloys.**
- **Subtask 1.4.4 – Initiate Rolling studies of FeNi MANC Alloys.**
- **Task 1.5– Evaluate Materials in FEM Traction Motor Design:**
- **Subtask 1.5.1 – Benchmark conductors in Traction HSM Design.**
- **Subtask 1.5.2 – Benchmark Metglas FeCo-based AMR in Traction HSM Design.**
- **Subtask 1.5.3 – Benchmark Metglas FeNi-based MANC in Traction HSM Design.**
- **Subtask 1.5.4 – Report Power Density Improvement with AMRs and MANCs.**

Summary

- Project seeks to demonstrate high speed motor efficiencies opening new markets for AMR and MANCs in traction motors.

- New MANC commercial production capabilities identified:

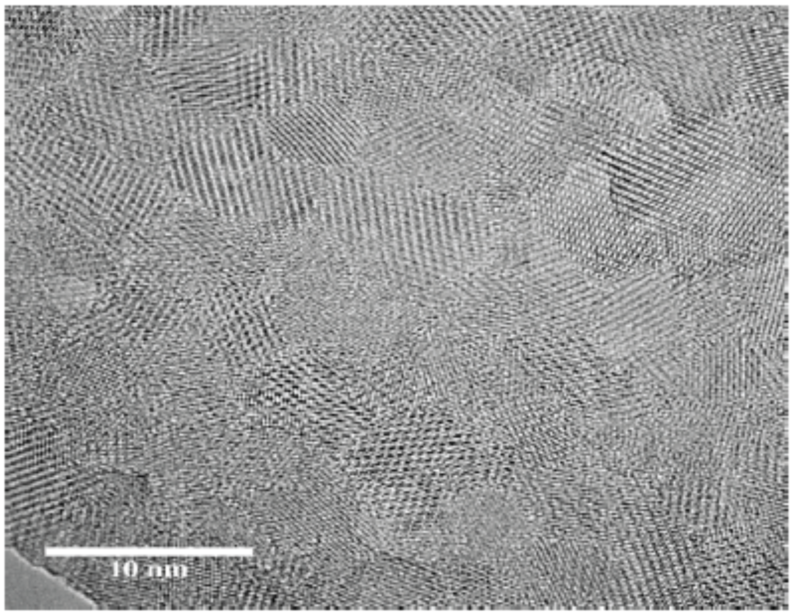
  Metglas has a license to test FeNi-base MANCs and has new FeCo-based AMRs.

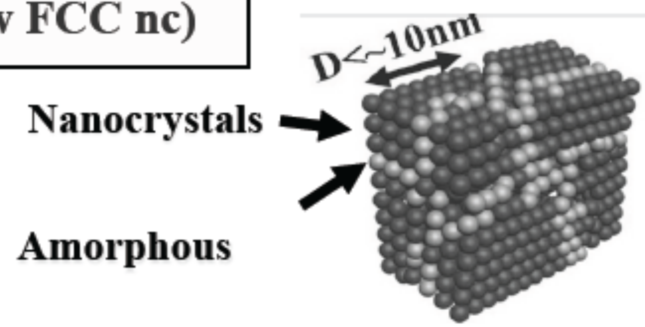
- Commercialization approach:
  - Technology transfer New Alloys to Metglas
  - Design new traction motor topologies.
  - Demonstrate potential scaling to 20 kW motors.
  - Identify permanent magnets and topologies with no use of heavy rare earth's.
  - Identify manufacturing methods of AMR's and MANCs for axial motor topologies.

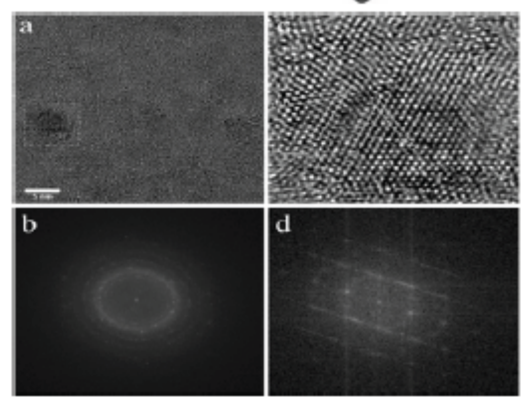
Technical Back-Up Slides

Technical Back-Up Slide

Metal Amorphous Nanocomposites (MANCs w FCC nc)







Ferromagnetic Nanocrystals Embedded in Amorphous Matrix (MANC):
Nanocrystals → High Induction
Matrix → Small Grain Size and Large Resistivity   Composite → Low Losses

Technical Back-Up Slide

Experimental: $(Fe_{70}Ni_{30})_{80}Nb_4Si_2B_{14}$

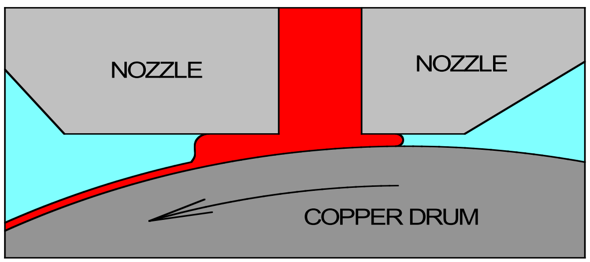
:

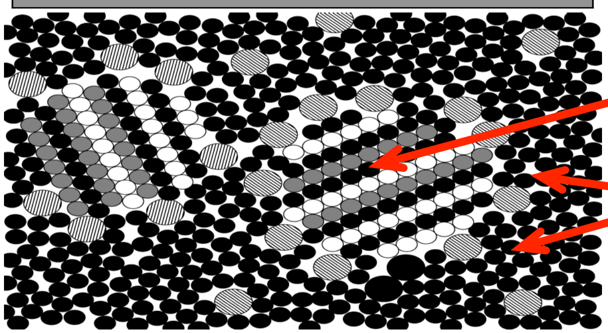
(MANC) alloys produced by PFC: TE = V, Cr, Mo, Nb

$(Fe_{70}Ni_{30})_{80-x}Nb_4Si_2B_{14}TE_x$ $(0 \leq x \leq 5)$ substitute for (FeNi)

$(Fe_{70}Ni_{30})_{80-y}Nb_{4+y}Si_2B_{14}$ $(0.5 \leq y \leq 2)$) substitute Nb for (FeNi)

Annealed at 440 °C and strain-annealed at 440 °C and 300 MPa





[6],[7], [14],[15]

TE = Early Transition Metal VBS Element

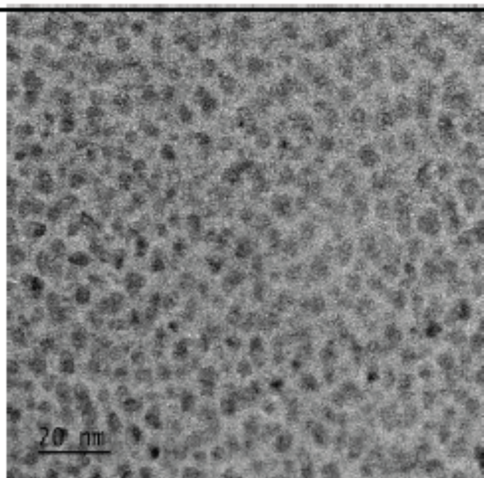
Resistivity from Am, NC phases and interfacial traps.

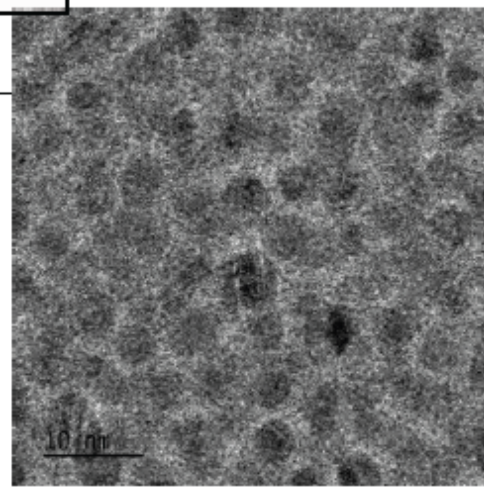
V, Cr are quite soluble in NCANDAMR

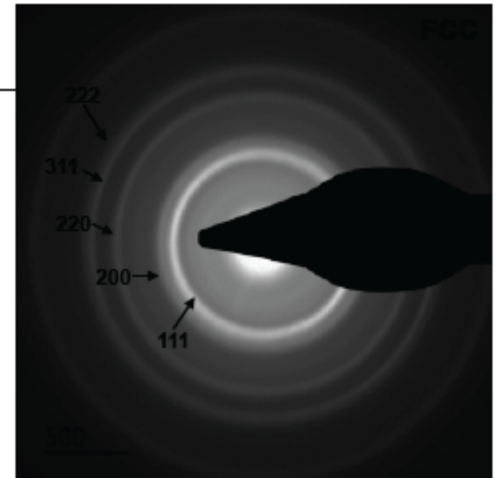
Mo, Nb are growth inhibitors interfacially trapped.

Technical Back-Up Slide

TEM of As-Cast 85% Alloy





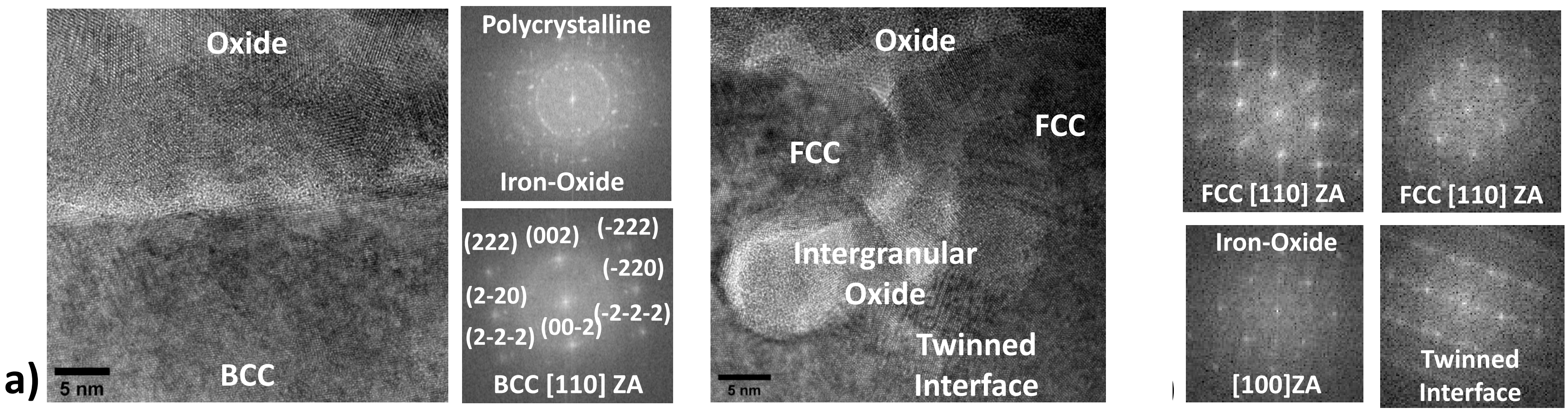


Mainly FCC Nanocrystals!

Wednesday
10:05 AM
Del Mar

Technical Back-Up Slide

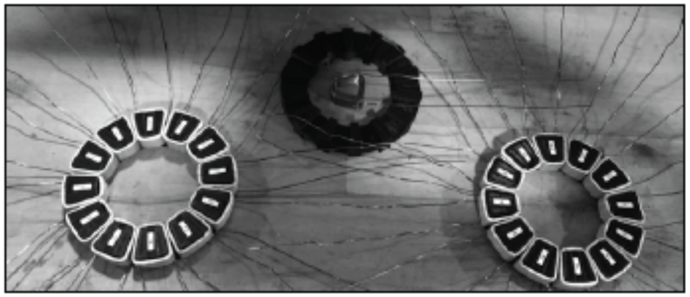
Air-Side Surface Characterization (HRTEM)

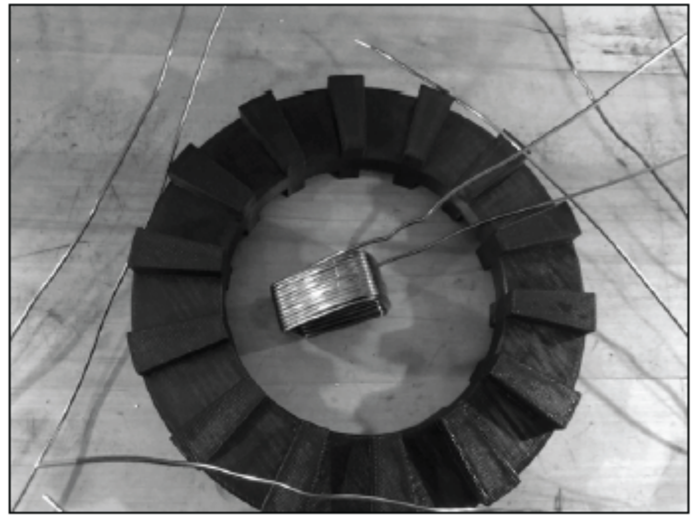


Polycrystalline Fine-Grained Surface Fe-Oxides and Intergranular Oxide Formation Between Surface Grains Forming a Mixed Region

Stators with coils and rotor

(3-d printed mock-up, > 50% wire fill factor)





rotor